A MIXED SOLAR CORE, SOLAR NEUTRINOS AND HELIOSEISMOLOGY

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Abstract

We consider a wide class of solar models with mixed core. Most of these models can be excluded as the predicted sound speed profile is in sharp disagreement with helioseismic constraints. All the remaining models predict ^{8}B and/or ^{7}Be neutrino fluxes at least as large as those of SSMs. In conclusion, helioseismology shows that a mixed solar core cannot account for the neutrino deficit implied by the current solar neutrino experiments.

I. INTRODUCTION

The hypothesis of a mixed solar core was advanced in the seventies as a desperate attempt to solve the solar neutrino puzzle of that time, i.e. the low signal reported by the Chlorine experiment in comparison with the Standard Solar Model (SSM) prediction [1–3].

Roughly speaking (see later for more precise statements) in mixed solar models the hydrogen content of the innermost region is enriched, so that nuclear fusion gets easier and the observed solar luminosity can be obtained at smaller central temperature. Correspondingly the ^{8}B and ^{7}Be neutrino fluxes should be strongly decreased.

It was clear since the beginnings that mixing was a hardly tenable hypothesis [4]. The Sun is a typical population I star and advanced evolutionary phases of solar like stars are observed in galactic open clusters. In the presence of an extended mixed core, the evolution of stars off the main sequence is altered in disagreement with the observed color magnitudine diagram of open clusters. However, the proposal of a mixed solar core could not be completely discarded in the absence of direct observational constraints on the internal solar structure.

In this respect, helioseismology provides a powerful tool [5]. Recently we have shown [6] that the sound speed near the solar center ($R/R_\odot \approx 0.1 - 0.2$) can be determined with an accuracy of few percent or even better. The predictions of mixed core models (MCMs) can thus be confronted with observational data. The results of a systematical analysis are presented in this note.

We remind that quantitative estimates of the neutrino fluxes predicted by MCMs were presented in [3,7]. Interest on this matter was revived recently by Cummings and Haxton [8]: by considering an artificial ^{3}He mixing with different upward and downward flow velocities, they found that the discrepancy between solar neutrino observations and predictions can be reduced. Bahcall et al. [9] have shown however that this model yields a sound speed profile drastically different from that inferred by helioseismology. In a similar context, Richard and Vauclair [10] considered local mixing induced by an anomalously large diffusion near the edge of the nuclear burning core, showing that the resulting models are incompatible with helioseismic data.

With respect to the previous literature, the main features of this paper are the following ones:

i) we take into account quantitatively the accuracy of the sound speed inferred from helioseismic data: in addition to the measurement errors, we consider the systematic uncertainties due to the choice of the starting solar model (used in the linearized inversion technique) and to the free parameters of the inversion algorithm.

ii) We systematically analyse sound speed profiles from fast and slow mixing models, for a wide choice of mixing region. We discuss both continuous and episodic mixing processes.

iii) As a result, we show that all MCMs which cannot be ruled out yield ^{8}B and ^{7}Be neutrino fluxes at least as large as in SSMs.

II. THE SOUND SPEED PROFILES OF MIXED SOLAR MODELS

We have studied the evolution of stellar structures by using the latest version of FRANEC [11]. Artificially, the internal composition is mixed, up to a radius R_{mix}. We have adjusted the original chemical composition and the mixing length so as to produce at the solar age ($t_\odot = 4.57$ Gyr [12]) the observed solar properties: luminosity, radius and photospheric Z/X. In this way we have produced (non-standard) solar models.

Firstly, we discuss in some detail the case of continuous mixing, i.e. the solar core is assumed to be mixed continuously from ZAMS to present.

We distinguish two regimes, by comparing the circulation time t_{circ}, i.e. the time needed for material circulation in the core, with the time scale of ^{3}He equilibrium abundance, $t_3 \approx 10^7$ yr. Following the classification of Ref. [2], we call "slow" ("fast") mixing that characterized by $t_{circ} >> t_3$ ($t_{circ} << t_3$).

In the slow mixing case the ^{3}He abundance is determined locally by its equilibrium value, while the abundances of H and ^{4}He are kept uniform in the mixed region. For the fast mixing, H, ^{3}He and ^{4}He are all kept uniform.

We anyhow assume that t_{circ} is much larger than the radiative transport time $t_r \approx 10^6$ yr (in the language of Ref. [2], we neglect "superfast" mixing).

Concerning the extension of the mixing regions, calculations have been carried out in all cases for R_{mix}=0.05, 0.1, 0.15, and 0.2 $R_\odot$.

In Figs. 1 and 2 we show (dashed line) the relative difference between the isothermal sound speed squared, $U=P/\rho$, as predicted by the mixed models and the helioseismic determination, $U_\odot$. The same quantity for our SSM is also shown (solid line).

The dotted area corresponds to the conservative uncertainty on $U_\odot$, as in ref. [6]. We remark that the accuracy of the helioseismic determination, although degrading at very small radii, is still better than 1% at $R/R_\odot \simeq 0.1$. Most of this (conservatively estimated) error [1] arises from the uncertainties of the inversion method; the observational errors on the measured frequencies contribute just an uncertainty $\Delta U/U \simeq 0.1\%$.

The predictions of acceptable solar models have to lie within the dotted area in Figs. 1 and 2, and actually our SSM (solid line) is generally in agreement with the helioseismic constraint.

On the other hand one sees a strong deviation of MCMs (with respect to $U_\odot$ and U_{SSM}) in the mixed zone; this is a consequence of the change in "mean molecular weight", μ, induced by mixing. In the approximation of perfect gas (accurate to the level of few per thousand in the solar core) one has $U \propto T/\mu$. Due to mixing, the innermost region is enriched with hydrogen, so that μ decreases (we observe that change of μ can be as high as 40%, whereas temperature change is at most a few per cent) and U increases. The opposite occurs near the edge of the mixed region.

As the mixing area increases the sound speed profile of the MCMs deviates more and more from the SSM prediction and it becomes in conflict with helioseismic constraint if $R_{mix} \geq 0.1R_\odot$.

We remark that the sound speed profile is altered also outside the mixing region (see Figs. 1 and 2 for $R_{mix} = 0.2R_\odot$), however this effect is weaker and provides a weaker constraint on R_{mix}.

Episodic mixing is another possibility which is worth studying, see also Ref. [7]. One assumes that once in the solar history a violent redistribution of material occurs, in a time shorter than t_3. Episodic mixing can alter significantly the subsequent stellar evolution, as its effects will be washed out only on a nuclear burning time scale, a few Gyr.

If episodic mixing occured early in the solar hystory, its effects are cancelled both on stellar structure and on neutrino fluxes, see Ref. [7]. On the other hand, a recent mixing should yield a stellar structure similar to that of continuous fast mixing. This expectation is confirmed by numerical calculations. In Fig. 3 we present the results of MCMs for $R_{mix} = 0.2R_\odot$, both for continuous fast mixing and for an episodic mixing occuring at $t = 4.54$ Gyr after ZAMS.

In conclusion, for the comparison with helioseismology the results of continuous fast mixing can be considered as representative of recent episodic mixing too.

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[1] We remind that our estimate of uncertaintes is very conservative because we add linearly the contibution of observational errors and of the systematical errors due to the inversion technique

III. NEUTRINO FLUXES

As the neutrino fluxes are strongly dependent on the central solar temperature T_c (see e.g. Refs. [14,13]), we first study the values of T_c in the continuous MCMs we have considered.

The behaviour of T_c as a function of the mixing radius (see Fig. 4) has been already exhaustively discussed in Ref. [2] for the fast MCMs. We find that also the slowly MCMs start increasing the central temperature, an occurrence which deserve some comments (being for slow mixing ^{3}He at local equilibrium values, the mechanism discussed in Ref. [2] cannot be at work).

Numerical experiments have clearly demonstrated that the case of slow mixing is governed by two conflicting mechanisms:

ii) the occurrence of a mixed region shifts the energy production at the center of the structure and consequently a smaller fraction of stellar matter is producing energy. To produce the same amount of energy the central temperature must increase. Note that this mechanism is reinforced by the fact that the energy is produced at smaller radii, so that the radiative flux (for a given energy output) is increased, increasing in turn the radiative gradient and as a consequence the temperature around the center quickly drops below the limit for efficient nuclear reactions.

ii) On the other hand, as in mixed models the core is enriched with hydrogen, nuclear fusion gets easier and this acts in decreasing the temperature.

From numerical experiments it is clearly shown that for a limited amount of mixing $(R_{mix} \leq 0.1 R_\odot)$ the first mechanism dominates and the central temperature increases. For larger mixing the increase of central H overcomes the first mechanism (i.e. the shift of the burning toward the center) and the central temperature starts decreasing.

The basic features of neutrino fluxes predicted by MCMs are shown in Fig. 5. They reflect the temperature behaviour mentioned above: if the mixed region is small enough both the intermediate energy (^{7}Be+CNO) and high energy (^{8}B) component are larger than the SSM prediction. Reduction of these components is obtained only for rather extended mixing, which, as shown in the previous section, are inconsistent with helioseismic constraint.

In conclusion helioseismology shows that a mixed solar core cannot account for the deficit of intermediate and/or high energy neutrino component, as implied by the current solar neutrino experiments (see e.g. Ref. [14]).

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FIGURES

FIG. 1.   For the indicated values of R_{mix}, we present the relative difference between the isothermal sound speed as predicted by solar model with fast continuous mixing, U_{mod}, and the helioseismic determination, $U_{\odot}$. The dotted area corresponds to the uncertainty on $U_{\odot}$.
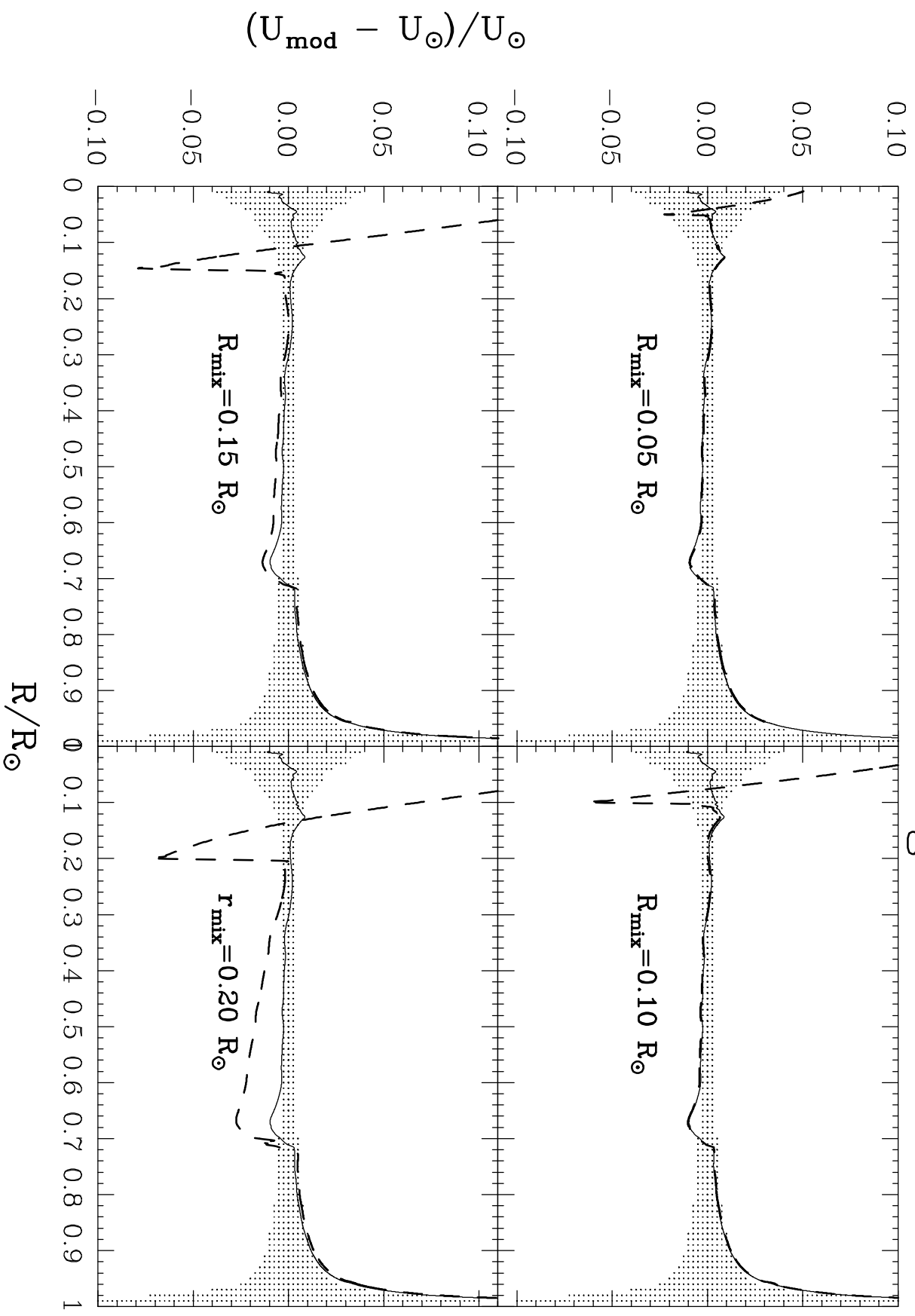
FIG. 2. The same as in Fig. 1, but for slow continuous mixing.

FIG. 3. The relative differences $(U_{mod}-U_{\odot})/U_{\odot}$ for solar models with fast continuous and episodic mixing (at $t = 4.54$ Gyr), both for a mixed region extending up to $R_{mix} = 0.2$ $R_{\odot}$. The dotted area corresponds to the uncertainty on $U_{\odot}$.

FIG. 4. The central temperature T_c of models with fast and slow continuous mixing as a function of the mixing radius R_{mix}.

FIG. 5.   The predictions of the intermediate (^{7}Be+CNO) and high energy (^{8}B) neutrino fluxes in solar models with continuous mixing, for the indicated values of R_{mix}. The prediction of our SSM (full diamond) is also shown.
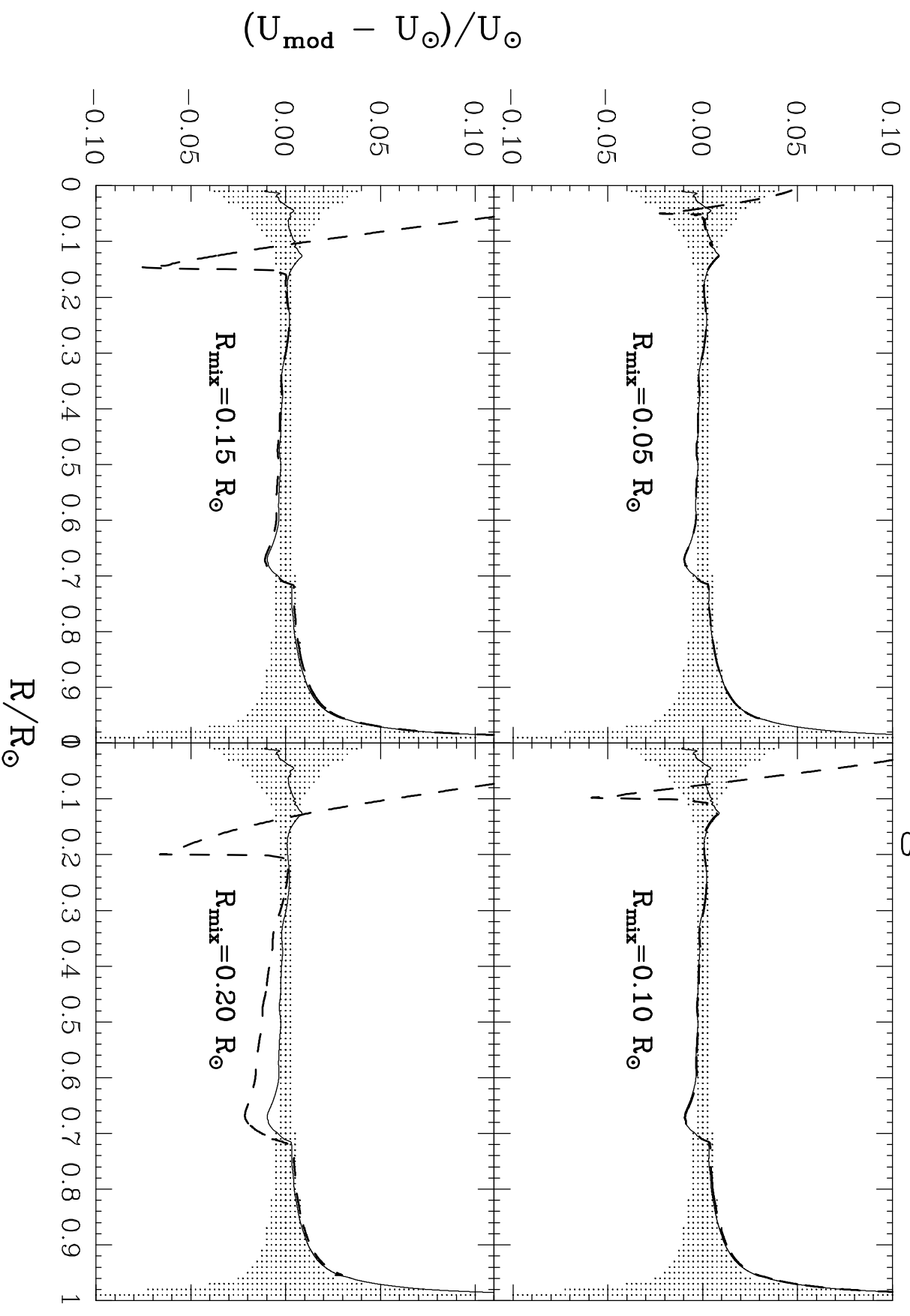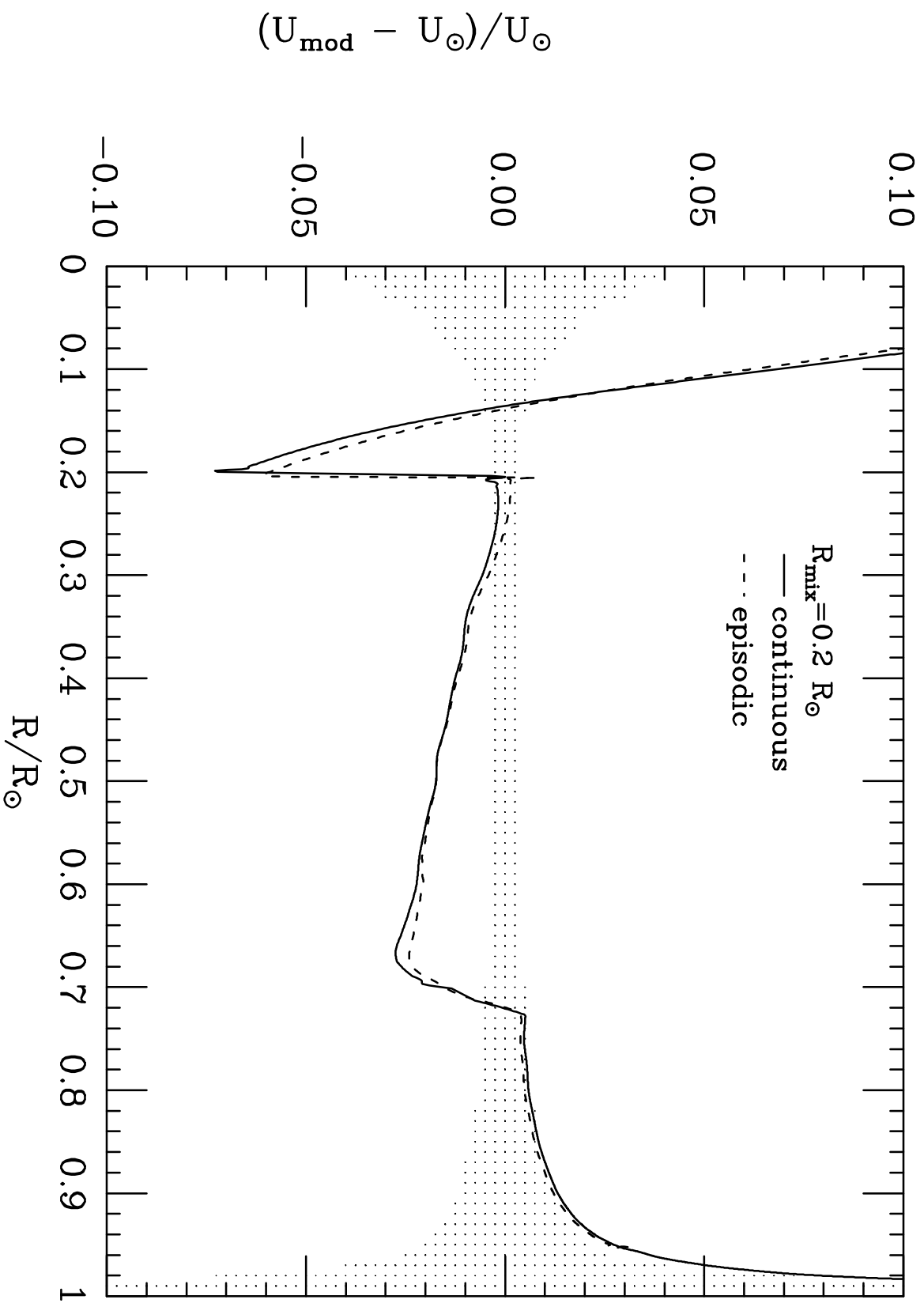
Fig. 1

Fast mixing

$R_{mix}=0.05$ $R_\odot$
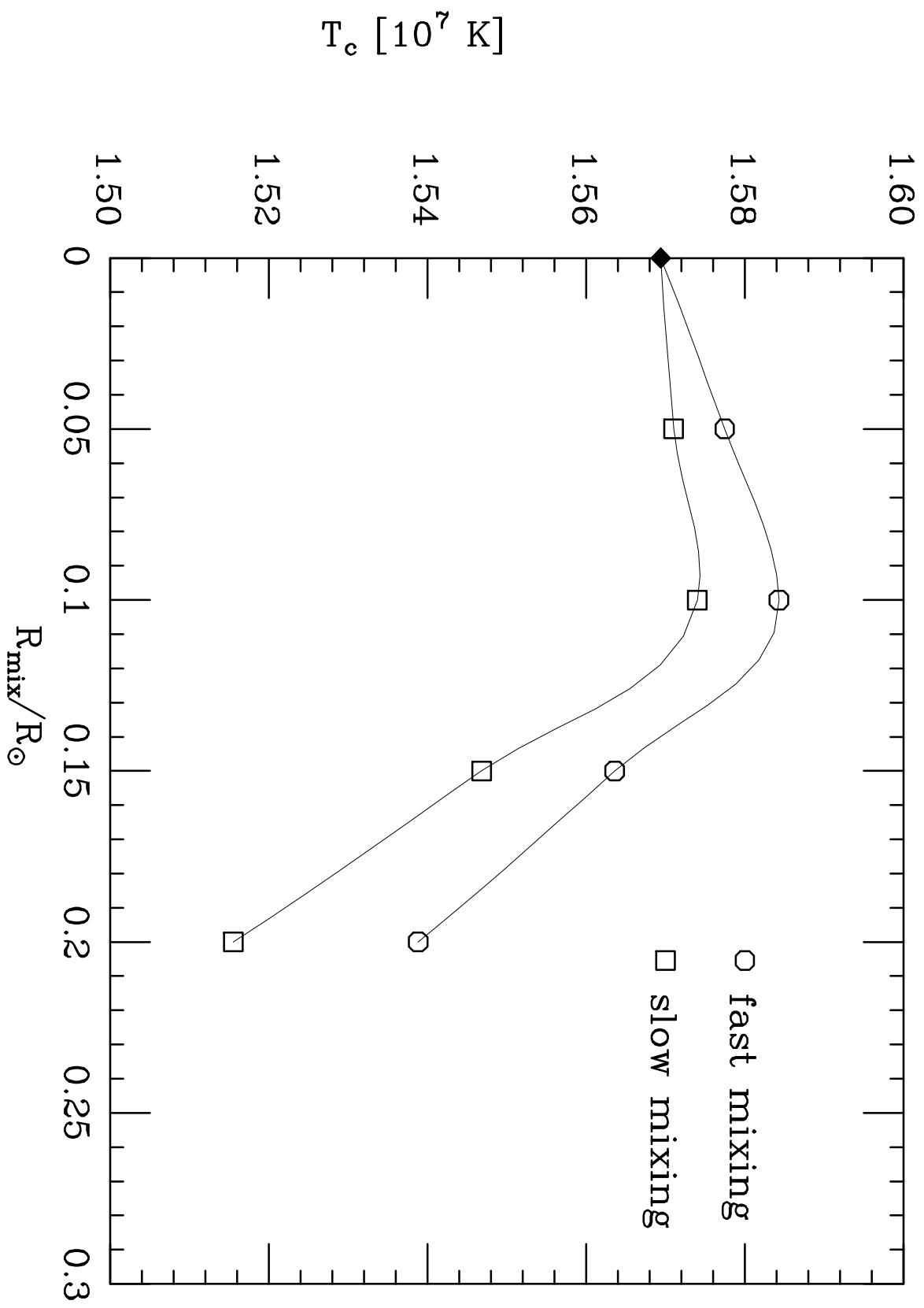
$R_{mix}=0.10$ $R_\odot$

$R_{mix}=0.15$ $R_\odot$

$r_{mix}=0.20$ $R_\odot$

$(U_{mod} - U_\odot)/U_\odot$

$R/R_\odot$

Fig. 2

Slow mixing

$(U_{mod} - U_\odot)/U_\odot$

$R_{mix}=0.05\ R_\odot$

$R_{mix}=0.10\ R_\odot$

$R_{mix}=0.15\ R_\odot$

$R_{mix}=0.20\ R_\odot$

$R/R_\odot$

Fig. 3

Fig. 4

Fig. 5